Understanding Edge Harmonic Oscillation Physics Using NIMROD

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Overview

• EHO background

• General reconstruction considerations
  – How do we determine the initial conditions for NIMROD?
  – Consideration of SOL profiles to avoid a discontinuous current

• Progress on EHO modeling
  – Nonlinear cases showing saturation
  – Current conclusions and future directions
Tokamak operation with edge harmonic oscillations (EHO) provides access to a quiescent H-mode regime [Burrell 2012]

- EHO: a small toroidal mode number \((n \approx 1-5)\) perturbation localized to the pedestal region [Burrell et al., PoP 19 056117 (2012) and refs within]

- Access to EHO operation regime requires control of the flow profile

- In particular, experimental observations indicate that the ExB flow shear is a key component in the generation of EHO [Garofalo et al., NF 51 083018 (2011)]

from Garofalo 2011
EHO drives particle transport

- Fluorine impurity transport studies find EHO provides as much particle transport as 40 Hz ELMs.
- Typically, core temperatures are increased with EHO

Comparison discharges on DIII-D from Garofalo PoP 22 056116 2015

Green – ELMing H-mode
Blue – QH-mode with EHO
Physical mechanisms of EHO are not fully understood

- Linear MHD calculations suggest EHO may be a saturated kink-peeling mode partially driven by flow-profile shear [Snyder et al., NF \textbf{47} 961 (2007)]

- Hypothesis: the saturated mode drives particle and thermal transport to maintain steady state pedestal profiles

- Why NIMROD?
  - Low-n mode requires global computations
  - Can model realistic x-point geometry
  - Drift stabilization built into model
  - Nonlinear capabilities

\[\text{Growth Rate (}\gamma^2/\omega_A^2)\]

\[\text{Toroidal Rotation Shear, } \Omega' \text{ (kHz)}\]

ELITE results from Snyder 2007
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Extended MHD codes start from state late in time within discharge

- Largest balance is $\mathbf{J} \times \mathbf{B} = \nabla p$ for magnetized plasmas
- Axisymmetric tokamak evolution is slow evolution of this force balance
- Experimentally: *Reconstructions* used to describe evolution
  - Use Grad-Shafranov solution constrained by experimental measurements to describe magnetic geometry and shape: EFIT dominant code
  - Routinely perform transport analysis to understand sources and fluxes from state to state
- How should extended MHD codes best model experiment given this paradigm?
  - Thesis: Requires understanding of reconstruction details, and sources/fluxes to eliminate free parameters and provide greatest value

Discharge with EHO from Garofalo 2015
Recent development: re-solve for fields from EFIT for numerical accuracy

- Enhancement to NIMEQ [Howell et al., CPC 185 1415 (2014)]
- Permits spatial convergence where mapped EFIT fields are first-order accurate
- Makes NIMROD more robust with (low resolution) experimental reconstructions
Reconstructions typically contain discontinuous current profiles across the separatrix

- Beyond separatrix: Current free
  - → No gradients in pressure
- EHO mode: large current drive (lives on the peeling boundary) and thus large discontinuity
  - Discontinuity is problematic for re-solves
  - Discontinuity is problematic for nonlinear NIMROD computations
  - Discontinuity is not physical
Towards more realistic modeling: Inclusion of SOL currents

- The experimental reconstruction doesn't set the gradient of thermodynamic quantities to zero on the LCFS because they aren't measured to be zero.

- Technical issues:
  - EFIT profiles only extend to LCFS
  - How do we extrapolate while minimizing free parameters?
  - Result should be as close as possible to known measurements
Currents (and flows) extend into the divertor.

- Force balance is enforced throughout the domain
- Divertor current limited to less than the ion saturation current (~$10^5$ A/m$^2$ for this case)
- Inclusion of SOL footpoints is of interest, but EHO mode dynamics are localized elsewhere
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We analyze DIII-D shot 145098 at 4250 ms while the discharge is ELM free with broadband EHO.

Initial state of computation
Current density and pressure and q profiles

- Our nonlinear computations use a single-fluid MHD model with anisotropic thermal conduction ($\chi_\parallel/\chi_\perp = 10^8$) with 24 toroidal Fourier modes.

- This computation is initialized from a linear two-fluid computations with full ion FLR effects (ion gyroviscosity and cross heat fluxes) of modes n=1-8 that is run until the largest linear perturbations reaches a magnetic energy amplitude of $2 \times 10^{-6}$ J.
Flow effects are known to be crucial to EHO.

\[ \mathbf{v}_{EQ} = \Omega_{E \times B} \mathbf{R} \hat{\phi} + K_p (\psi) \mathbf{B} + \Omega \nabla_p \mathbf{R} \hat{\phi} \]

- Flows are specified by the reconstruction up to the separatrix and extrapolated to zero beyond the separatrix at the SOL-current-free interface.
Mode amplitudes saturate to a turbulent state

- $n=5$ dominant (along with $n=4$) during linear $[0-0.3 \times 10^{-4} \text{s}]$ and saturation $[0.3-0.5 \times 10^{-4} \text{s}]$ stages
- $n=2$ dominant (along with $n=1$) later $[0.5-0.9 \times 10^{-4} \text{s}]$
- Final state of computation has $n=1, 2, 4, 5$ at comparable amplitudes
- Need to run cases long (ms time scale)
- Still need higher resolution and/or FLR stabilization to resolve higher-$n$ modes
Pressure evolution

- Movie for $t > 2.45 \times 10^{-4}$s
- Initially coherent eddies develop
- Turbulent state develops at $t > 0.5 \times 10^{-4}$s
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See:
https://www.youtube.com/watch?v=cOEZ8gAVPUk
Current evolution

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- Significant current-density dynamics with reversed current regions
- More resolution is needed to capture dynamics during the peak amplitudes saturation phase
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Stochastic fields with homoclinic tangle are present in the simulation.
Dynamic profiles are computed with a n=0 line-out on the outboard midplane.

Line out for axisymmetric profile plots.
Final density transport is large compared to temperature transport

- Result is surprising with stochastic fieldlines and large anisotropic thermal conduction
- But this result is qualitatively consistent with experimental observations
- More study is required: phase correlation effect?

\[
\Gamma^n = \langle \tilde{n} \tilde{v} \rangle \\
\Gamma^T = \langle \tilde{T} \tilde{v} \rangle
\]
Modifications to the flow profiles are small

- Toroidal rotation profile is essentially unchanged
- Poloidal rotation is modestly modified during the peak amplitude phase, but returns to nearly the initial state for $t \geq 7 \times 10^{-5} \text{s}$
Open questions

- What is the saturation mechanism?
  - Profile modification through relaxation?
  - Coupling to higher-n modes? [Do we need to include FLR drift stabilization?]

- How does the modeled perturbation compare with measurements?
  - Near term: Compare with magnetic coil measurements
  - Long term: Compare with BES measurements

- Can we model the transport caused by the EHO?
  - Related to the saturation mechanism through profile modification
  - Many subtleties here: next slides
Transport effects are subtle but critical

- Reconstructed profiles include the effects of EHO transport
- Implicit transport contained within the reconstruction:

$$\frac{\partial X}{\partial t} = -\nabla \cdot (\Gamma^X_{\text{neoclassical}} + \Gamma^X_{\text{turbulence}} + \Gamma^X_{\text{EHO}}) + S^X = 0$$
Need future studies to characterize EHO transport

- NIMROD models the evolution of 3D, nonlinear perturbations with the extended-MHD model around 2D state
  - These perturbations self-consistently modify the axisymmetric state
  - Major complication: the reconstructed state includes transport from the 3D perturbations

- Currently, we are double counting $\Gamma_{EHO}$ (once from NIMROD and once in the reconstruction)

- Cancel out $\Gamma_{\text{NIMROD}}$ with an ad-hoc source for a consistent model?
  - Does this preclude saturation through profile modification?

- Can we check that $\Gamma_{\text{NIMROD}} = \Gamma_{EHO}$?
  - Need to know all other sources and fluxes to test
Summary

• Initial state is based off an EFIT reconstruction
  – We re-solve the Grad-Shafranov equation with open fieldlines consistent with NIMROD's basis functions
  – Modeling with a SOL eliminates edge current/flow discontinuities

• Preliminary EHO results are tantalizing:
  – Nonlinear modeling produces a saturated turbulent-like state
  – Mode preferentially produces density transport
  – Need to run simulation longer and at higher resolution

• Much more to study:
  – Experimental (magnetic coil) comparisons
  – Saturation mechanism
  – EHO transport